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Manufacture and characterisation of prototype straw bale insulation products

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Abstract

This paper presents the development and characterisation of prototype wheat straw bales that have been produced specifically for use as a building insulation material. Although straw bales have been used in construction for over a century their use still remains niche in the wider construction market. Whilst traditional straw bales can be used for either loadbearing or non-loadbearing applications, it is their thermal resistance that is of greatest benefit to building performance. There is great potential to significantly improve the thermal resistance of straw bales for construction by reconfiguring the baling process to orientate the straws preferentially, and also produce bales sizes more suited for contemporary construction practices. Laboratory scale baling equipment has been developed to produce prototype bales with straws optimally orientated for thermal resistance. Computer Tomography has been applied to investigate the internal structure and orientation of agricultural and prototype straw bales. Changing orientation of the individual straws improves thermal resistance by 28%, facilitating thinner walls, and enabling greater uptake of a novel low embodied carbon bio-based material into mainstream construction.

Keywords: Straw bale, thermal conductivity, insulation, computer tomography, compression resistance

1 Introduction

Interest in using bio-based building materials has grown in recent years as more sustainable solutions for construction, with lower embodied carbon emissions, are sought. Although straw stalks from various cereal crops has been used in construction for millennia, the use of compacted bales to provide insulation is widely cited to have begun in the nineteenth Century in Nebraska, USA, with the advent of mechanical baling machines [King, 2007]. Although straw bales have favourable insulation properties, and can be stacked to build modest load-bearing walls, they are currently produced for the convenience and needs of agriculture rather than the requirements and demands of a potentially higher value construction market. Consequently, the use of straw bales in building remains niche and largely unregulated in the absence of standards and codes of practice.

During harvest, mechanised combine harvesters collect the cereal grains and deposit the cut straw stalks in the field. Baling machines subsequently collect the cut cereal stalks, compress and tie the straws into individual bales. Baling usually occurs directly in the field shortly after harvesting the cereal crop. The straw bales most commonly used in construction measure between 900 and 1000 mm long, 450 mm wide and 350 to 375 mm high (when laid flat), produced in densities between 100 – 150 kg/m^3. In recent years larger, and higher density, rectangular and round bales have become more common place [Lecompte & Le Duigou, 2017]; although less suited directly to construction purposes these jumbo bales can be re-baled into the smaller traditional sized bales for use in building. Rendered straw bale walls 450 – 500 mm thick provide sufficient mechanical resistance to build 1 to 2 storey high load-bearing walls as well as providing excellent thermal insulation and good acoustic resistance. Well compacted rendered bale walls also provide remarkably good fire resistance [Wall et al, 2012]. However, baling processes developed for agriculture produce bale sizes that are not ideally suited for wider construction uses, particularly as insulation in timber framed construction, and perhaps more significantly orient the straw stalks in directions that do not maximise their potential thermal resistance [Shea, A., et al., 2013].

Previous work has shown, within the usual range suited to construction, that the thermal conductivity of straw bales is relatively independent of density [Shea et al., 2013]. However, various researchers have shown that bale thermal conductivity values are highly orthotropic [McCabe, 1993; FASBA 2009; Yao, 2015]. When agricultural bales are used in construction, laid either flat or on edge, the straws are predominantly oriented parallel to the direction of heat flow. In this orientation measured thermal conductivity is in the range 0.060 - 0.067 W/m.K [Shea, A., et al., 2013; Douzane, O., et al., 2016]. These thermal conductivity values are up to twice those with competing products such as mineral wool and natural fibre solutions such as hemp and sheep's wool, requiring twice as much insulation to achieve the same thermal resistance. However, when the straws are aligned perpendicular to the direction of heat flow, the measured thermal conductivity reduces to 0.043 - 0.045 W/m.K [Yao, J., 2015], a potential reduction in wall thickness of 35% for the same insulation performance. The lower conductivity values have been derived from small specimens in which all the individual straws were oriented, by hand, perpendicular to the heat flow [FASBA, 2009; Yao, J., 2015; Douzane, O., et al., 2016]. By reconfiguring the baling machine process there is clearly an opportunity to improve the thermal resistance of straw bale insulation and increase its use in construction [Véjeliené, 2012].

The aim of the research presented in this paper has been the development of novel straw bale insulation products through modification of the baling process. To meet this aim, specific research objectives have been: development of a laboratory prototype baler and baling process;

thermal and internal structural characterization of baled wheat straw; and, investigating thermal and compression resistance performance of the prototype bales. The prototype bales have been developed for mainstream construction as a non-loadbearing insulation product.

2 Straw bale production

A variety of cereal crop straw is suited for straw bale construction, but the most common in Northern Europe is wheat straw, which is generally available at lower cost and is least preferred for other uses such as animal feed supplement. Straw from oats and barley are also suitable within Europe, while rice straw is often used within Asia and is also ideal as it has very good durability due to its particularly high hydrophobic silica content.

To produce rectangular bales, the baler picks up the windrows (long lines of racked straw deposited by the harvester for drying), which are fed into a compaction chamber by a large screw. A rapidly moving head compresses the straws into 100 – 150 mm layers or “flakes”. The flakes continue to be compressed until a desired length is reached before being wrapped in twine, tied off with by a knotter, and ejected back onto the field. The height and width of the bale are determined by the compression chamber dimensions, commonly 450 mm x 350 mm for traditional rectangular bales. The length is the most variable dimension, with density also set by the baler. The mechanics involved in producing a straw bale are in-part affected by the properties and conditioning of the harvested material [Mathanker & Hansen, 2014].

Limited past studies on the construction application properties of agricultural bales [Maraldi et al., 2016] and rendered straw bale behaviour [Ashour et al., 2011] have concentrated on mechanical performance, and in particular the importance of density to performance. Other wider research on densification of straw has been related to transport and the production of bales as bio-mass fuel [Heldman, 2003; Kaliyan and Morey, 2009; Zhang X., et al., 2018]. It is evident that densification permits more material mass to be transported in a particular volume as well as facilitating handling and durability, however, as previously noted the thermal insulation benefits of greater densification are limited.

Agricultural baling machine mechanics is a complex system of variables with a focus on bale density as the production output. Production pressure, temperature, processing speed and straw properties, such as length and moisture content, have been identified as key factors in baling [Kaliyan & Morey, 2009]. Efficiency of the baling machine is largely dependent on these variables and their impact on bale production for a particular density. As straw is compressed within the chamber a lateral force is also exerted onto the chamber walls, resulting in side friction. Research conducted by O'Dogherty (1989) reports work from 1959 (undertaken by Mewes) where a model baling chamber was used to investigate baling mechanics. It was reported that the lateral pressure exerted during compression of straw reached values of up to 36% of the applied axial pressure. It has subsequently been estimated that only 37 – 40% of the baling energy is required to compress the bale with the remainder needed to overcome the frictional forces along the chamber walls.

3 Experimental materials and methods

In this study the mechanical and thermal properties of agricultural and prototype wheat straw bales were studied, including an investigation of straw orientation on the thermal and mechanical properties. Computer Tomography (CT) scanning was used to investigate the internal structure of the bales. The process used to manufacture prototype straw bales is outlined Section 4 of this paper.

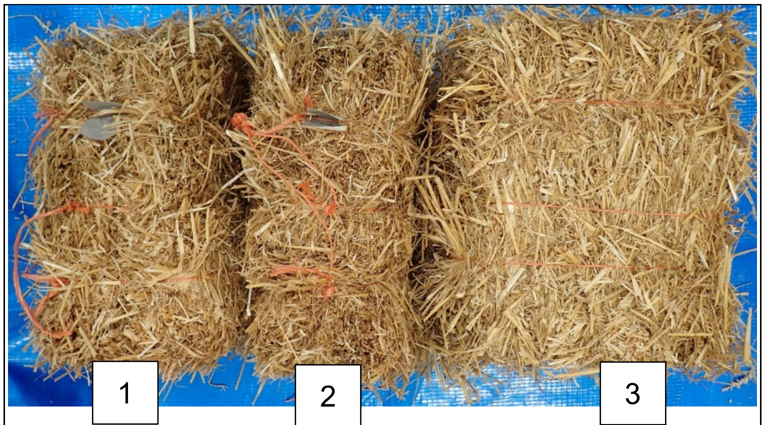
3.1 Wheat straw

Agricultural wheat straw bales were purchased from a farm in Keynsham, Somerset, UK in 2018. All the bales used in this investigation were purchased from same supplier and batch.

3.2 Computer Tomography

Computer Tomography (CT) was used to investigate the internal structure of the agricultural and prototype straw bales. Scans were taken using Nikon's XT H 225 ST system designed for industrial CT scanning. X-rays from a 225-kV source penetrate a rotating body producing a series of 2D images are produced about a central point. Each slice is an image made up of picture elements (PIXELS) and volume elements (VOXELS), which are the slice width times the area of the PIXEL. As the object is rotated, the resulting slices produce a cylindrical volume. This process will, in some cases, leave an edge or striated affect along the sides of the cylinder.

On larger objects, the scanning volume is likely to be a sub-volume of the original size. The slices are then used to build a three-dimensional graphical representation of the internal structure of the bales without disturbing their internal structure. However, as the CT Scan chamber used has limited size, an individual agricultural bale measuring 400 x 350 x 850 mm (D x H x W) was sectioned into three parts representing the central and end cross-sections. Using a baling needle and new twine, the original agricultural bale was sectioned off while the original twine remained to maintain the original confinement and density of the straw bale. Once the sections were individually tied off with the new twine, the existing twine was cut resulting in three new specimens. The specimens measured approximately 400 x 350 - 400 x 225 mm (Figure 1). Whilst the forming process may have caused some disturbance to their edges, it ensured the central portion of each specimen remained intact. The CT scan was focused on the centre of each bale section and the data was analysed using Avizo software enabling inspection of the straw bale internal structure non-destructively and so assess the degree of individual straw orientation relative to the forming process of the bale.



1 – End section	2 – Central section	3 – Half bale
W ≈ 225 mm *D ≈ 350 mm* *H ≈ 400 mm*	*W ≈ 225 mm* *D ≈ 350 mm* *H ≈ 400 mm*	*W ≈ 400 mm* *D ≈ 350 mm* *H ≈ 400 mm*

Figure 1 – Agricultural bale sections

3.3 Impact of straw orientation on compressive resistance

Although the focus of this research has been to optimise the baling process to improve thermal resistance, compaction will also impact the bale compressive resistance properties. Standard agricultural bales exhibit anisotropic behaviour in compression [Vardy and MacDougall, 2006]. Although the proposed use of the prototype bales is as non-loadbearing infill insulation placed between timber studs, a minimum compressive resistance, in part to ensure that there will be minimal insulation settlement after installation, is necessary. Methods outlined in BS EN 826 (2013) were used to assess the strength and strain characteristics of the prototype straw bale. After conditioning at 23 °C and 50% RH for 24 hours, individual 150 x 150 x 400 mm test specimens with a density of 120 kg/m^3 were loaded using a 50 kN Instron Universal Testing Machine. The load was applied through with a 150 x 150 x10 mm steel plate placed above and below the faces perpendicular to the direction of compression to be tested (perpendicular or parallel to the compressive force during the bales production). The steel plate provided a 1.9 kg preload as well as distributing the load over the area to be tested. The individual bales were subject to uniaxial compression loading under a constant displacement rate of 0.1 *d* per minute, where *d* is the depth of the bale specimen in the direction of loading.

3.4 Influence of straw orientation on thermal performance

The thermal conductivity of two straw bale prototypes were measured using a heat flow meter apparatus following ISO 8301:1991. Prototype oriented straw bales were initially produced at 400 x 100 x 100 mm; a larger bale assembly for thermal testing was formed by tying together four prototype bales to form specimens measuring 400 x 400 x 100 mm. The larger bale assemblies were then reloaded into the press and re-compressed with the same formation load of 40 kN. Additional prototype bales were prepared for testing by cutting the oriented straw bales down to 100 mm lengths, producing 100 x 100 x 100 mm bale sections. These bale sections were loaded into the press rotating their direction by 90 degrees so that the straw was oriented parallel to the intended heat flow and again re-compressed a 40 kN load before tying off. Each of these bale packages was dried at 105 °C until stable mass was reached and then conditioned at 23 °C and 50% RH for 72 hours. The bundles were then wrapped in thin plastic film prior to loading into a Fox Instrument’s F600 Heat flow meter, to help maintain conditions during the tests. The thermal conductivity tests were run at 20 °C mean temperature gradient with lower and upper limits of 10 °C and 30 °C.

4 Development of baling method

Production of the oriented prototype straw bales used laboratory scale equipment and materials developed for the purpose. Various factors were considered in development of the processes, including: shape; density; and, stem orientation related to ease of production mechanics. Whilst shape and dimensions were informed by the limitations of the available laboratory equipment, scale compared to existing insulation materials and construction methods were also considered. The process was further refined during early stages to ease of production and achieve density objectives.

Initially both vertical and horizontal compaction methods were developed, using moulds with widths of up to 400 mm and 100 mm or 150 mm height. The cross-sectional dimensions were governed by the requirements of specimen sizes for testing as well as future practicalities of construction with respect to conventional timber stud dimensions.

The wheat straw required to make these prototypes was taken from the agricultural bales, initially sifted to remove dust, and then manually placed into the compaction chamber. The very low stiffness of the loose straw requires relatively large jack displacements to achieve the required density. However, the stroke on the compaction jacks is limited, which was difficult to overcome in the vertical arrangement, but was more achievable with the horizontally loaded chamber using multiple jacks in series (Figure 2). As the straw is compressed in the chamber, pressure increases on the baling twine and excess lengths of twine gets tangled within the straw. At forces required to produce a stable bale, the twine is completely captured and friction forces exceed that of the tensile strength of the twine resulting in broken twine or loosely tied off bales. To ease the friction induced on the baling twine while tying off the completed bales with a Miller's Knot, a series of slots and grooves were cut into each face of the chamber as seen in

Figure 3. These slots accommodate the gathering of the twine as the chamber volume is reduced as well as minimizing the lengths of twine under high friction forces or entanglement.

Figure 2. Horizontal laboratory scale baler during production

Figure 3. Closed chamber with slots for twine

Trials to produce specimens of prescribed density were based on the observed physical performance of the oriented straw bales. Lower densities, compression forces, and time under load would result in a relaxing or ‘rebounding’ effect with the bale expanding to such an extent as the bale could simply fall apart. In other cases the strings would maintain localized compression with the remainder of the bale expanding creating ‘mounds’ in between. This mounding effect would result in large gaps in the insulation and therefore was unacceptable for further testing. Bales that did not relax greater than 5% of their final production depth after 48 hours were considered sufficiently stable for further testing. The determined compressive pressure of 650 kN/m^2 was applied for at least 60 seconds (approximately the time it takes to tie off the bale while under load) for all prototype bales produced in this study. In trials it was evident that bales could only be reliably produced using width to height ratio of not greater than two. Beyond this the bales curled up or rounded when tied with the baling twine (Figure 4).

Re-baled straw specimen
Compressive load: 40 kN
Initial dimensions: 800 x 150 x 400 mm
Compact dimensions: 80 x 150 x 400 mm

Figure 4. Oriented re-baled straw

When compressing the oriented straw prototype within the confined chamber, there is an initial bulk deformation that takes place. This is mostly the expulsion of air from between the stems. As this space decreases, the force acting upon the stems increases resulting in an initial elastic deformation of the bulk straw. Increasing the force with then begin to oval the stems and more air is dispersed from the bale resulting in large plastic deformations. Within the confined space of the baling chamber the walls and internal friction between the stems provide an increased reaction force. As the stems ovality increases they begin to “slip” past each other into layers. At this point the reaction force rapidly decreases and elasto-visco-plastic deformation occurs. This process produces an anisotropic bale relative to the formation load. Further increases in pressure on the bale continue to expel air and increase bale bulk density, stiffness, and compressive resistance. Beyond this point, any further compressive force would cause failure of the stems with little to no air left within the bale, therefore increasing its thermal conductivity as it approaches a solid form. The compression of agricultural products has previously been investigated and can be mathematically represented by models such as the Faborode, Maxwell, and Peleg models [Nona et al., 2014].

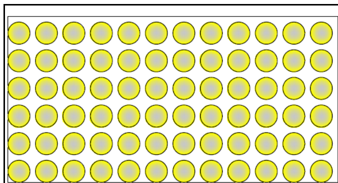
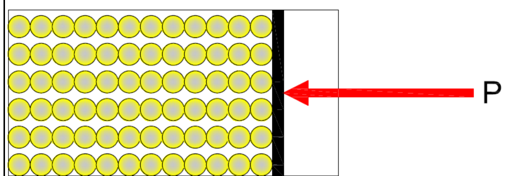
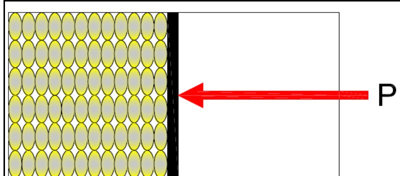
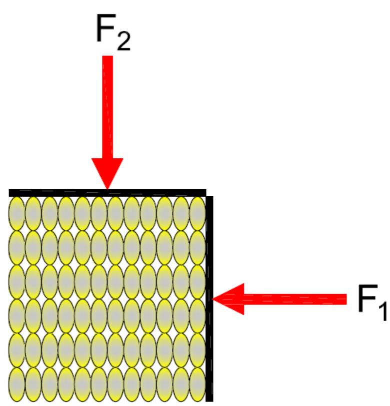
	Loose straw is loaded into the chamber
	Straw is compressed inside the chamber
	Straw begins to deform under high compressive production load (P)
	Compression resistance testing was completed for two separate series of randomly selected prototypes. The first series was tested with loading (F1) parallel with the production load (P). The second series was tested with loading (F2) perpendicular with the production load (P)

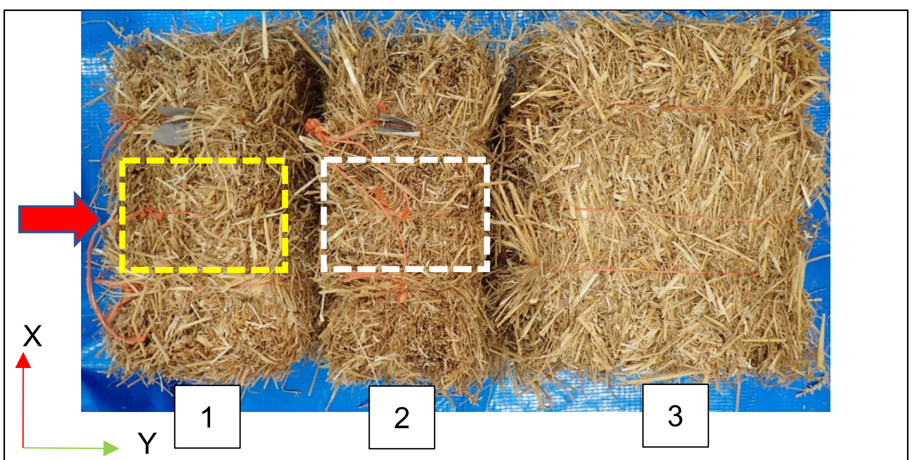
Figure 5. Straw interaction during compression

5. Results and Discussion

5.1 Orientation of straw within a bale

Orientation of straw stalks within the sections taken from standard agricultural bales and the prototype oriented straw bales were assessed by using Nikon's XT H 225 ST Computer Tomography (CT) system. The parameters for the scans are as follows: 137 ua; 152 kv; 0.5 sec exposure; No filter; 180 projections; 2 averages; 24 gain; Tungsten target.

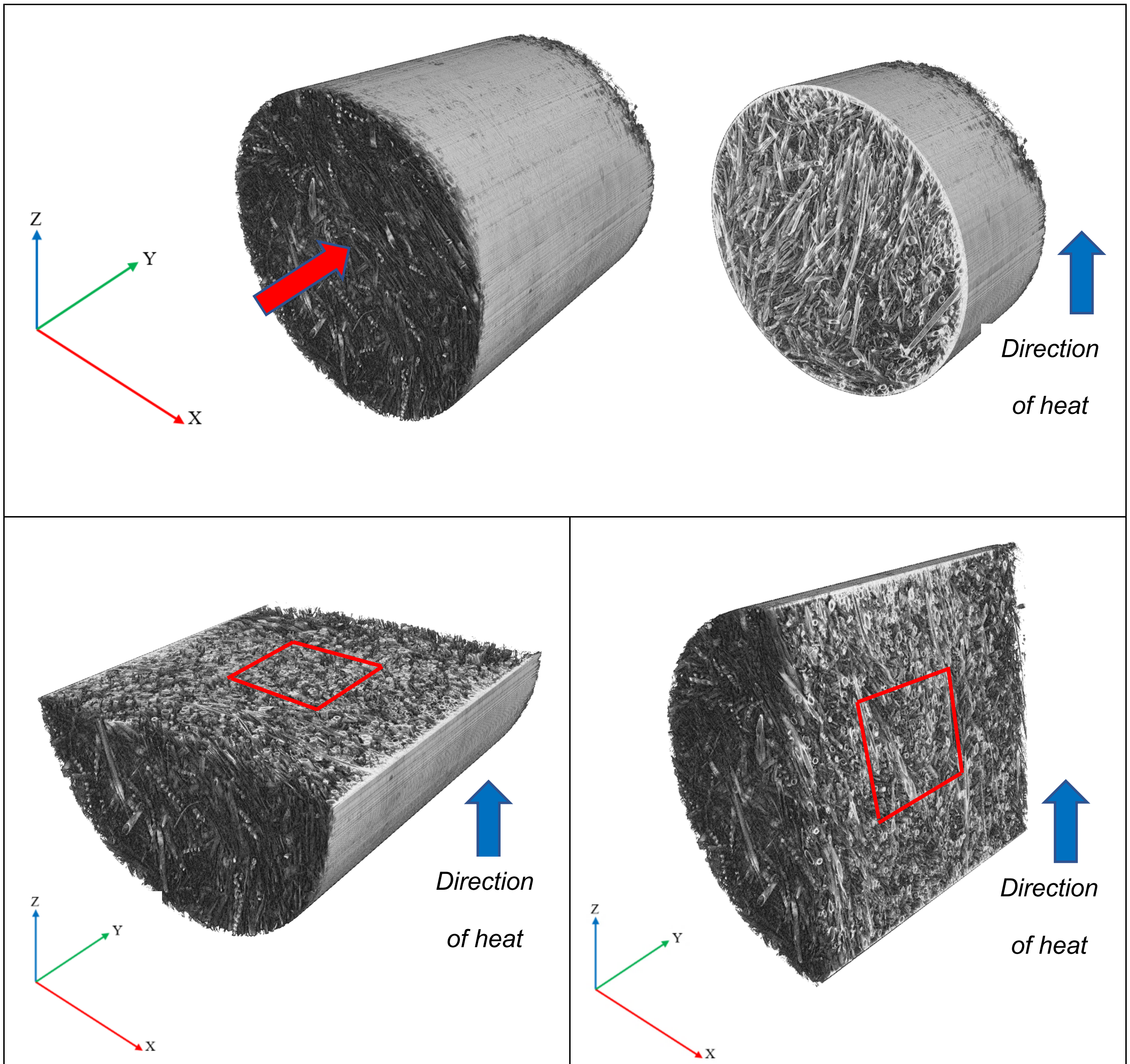
An approximate scanning volume of 200 x 250 mm (Dia. x H) was reconstructed from the centre regions of the two smaller 400 x 350 x 225 mm (D x H x W) sections of the agricultural straw bale. The dotted lines in Figure 6 indicate the approximate volume, with the red arrow showing the pivot about which the scans were taken (for these bale sections, the scans were completed with them laying down and the arrow pointing towards the CT bed).



1 – End section	*2 – Central section*	*3 – Half bale*

Figure 6. Agricultural bale sections (pivot of scan indicated by red arrow)

The scanned sections from Figure 6, shown in Figures 7 and 8, display the direction of the straw in the centre of each scanning volume. For this representation, the heat flow in the traditional straw bale construction would be along the x-axis in Figure 6. Straw oriented across an image presents as a series of long lines whereas straw oriented through the image presents as circles representing the ends of the stems. The degree of ovality displayed is a result of stems at an angle to the plane shown and short lines or ellipse with high degrees of ovality show ends of split or compressed stems. The Avizo software package used in the analysis provides an array of tools to obtain the best image possible. For a straw bale, this leaves a very tight margin from which various parts of the straw stems are discernible in the image. When the bales are compressed to higher densities as in the oriented prototype, that margin decreases even further. For the agricultural bale, a grey-white colour scheme highlights the ends or edges of the straw (lighter areas) best relative to air or lower density areas (darker regions). Note that the axis shown are based on the placement in the CT scanner and not through the bale. The direction of the heat flow through the bale is represented by the blue arrows relative to the original location within the bale which in this case is the z-axis.



Sub-volume cross section (xy axis)

Sub-volume cross section (yz axis)

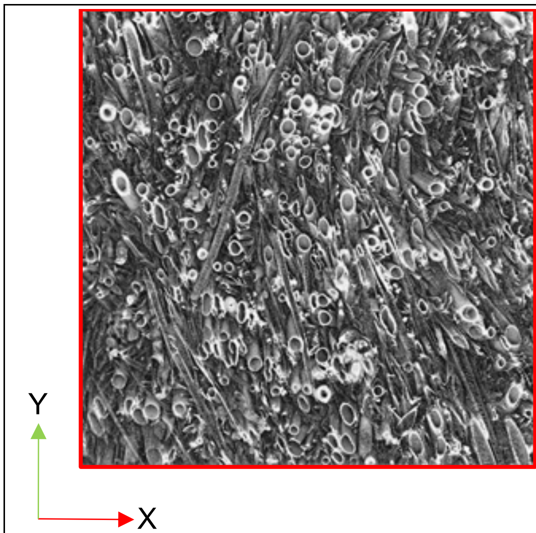
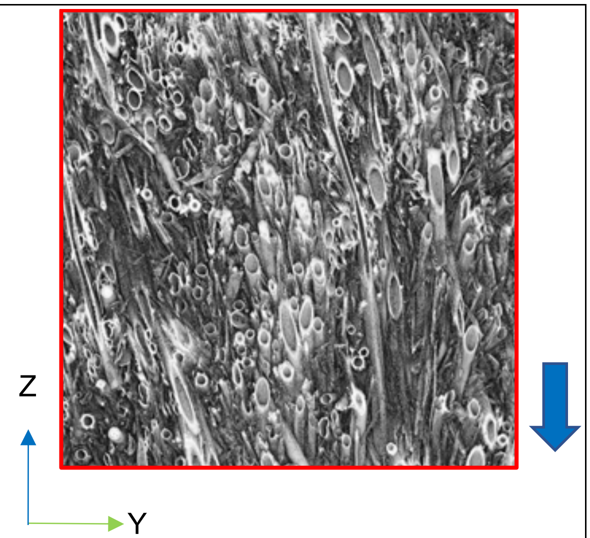
	
Direction of heat flow ***through*** *image, image looking through the height of the original bale (vertically)*	*Direction of heat flow* ***across*** *image, image looking through the depth of the original bale (horizontally)*

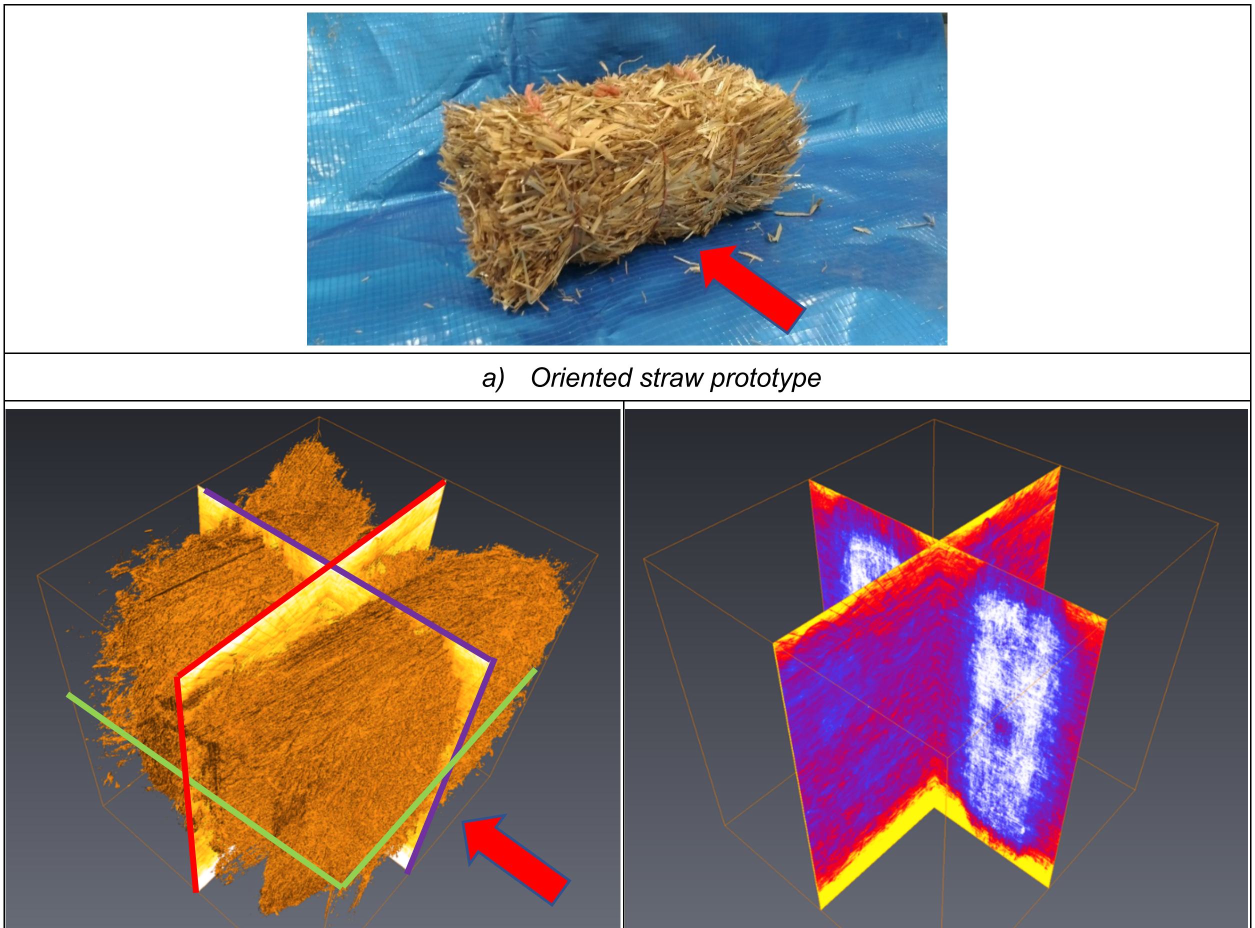
Figure 7. Section 1 CT scan (bale end section)

The CT scans of the two regions within the agricultural bale show the directionality of the straw stems in that region. A clear difference in directionality is evident in the end region while, in this case, the interior of the bale is more mixed. The interior region shows both round, longitudinal, and oval shapes indicating a variety of directions. This may be attributed to the process of large-scale baling equipment where the screw feed is rotating the stems as they are fed into the compression chamber, resulting in a mixed or rotating stem direction. As the scans focused on the middle 200 mm diameter, the directionality may differ towards the exterior regions as would be expected based on visual inspection of a traditional bale.

The prototypes were scanned in the same manner as the larger agricultural bale sections with the exception of a smaller more focused scanning volume, approximately 150 x 150 mm (Dia. x H), as permitted by the smaller scale of the bale. As the new bale is formed, a smaller series of ‘flakes’ begin to develop as the straw is compressed. In the smaller sections, these flakes originate in folds likely due to the way the straw was handled in loading the chamber. These folds can be seen in the cross section of one of the prototype bales shown in Figure 8.

Figure 8. Half section of oriented straw bale

The CT scan, as before, was produced about a central point as the prototype was rotated within the scanning chamber and is indicated by the red arrow in Figure 9a. As seen in Figure 9b, although there are still some smaller pieces of straw randomly oriented, the three dimensional image created from the CT scan shows a highly directional formation. Figure 9c further supports the presence of the flakes from the folds. As the flakes are formed, higher density regions are created within each fold. This is clearly observed in the cross-sectional view displaying the localized effect of the flake formation with the white areas indicating a higher degree of density.



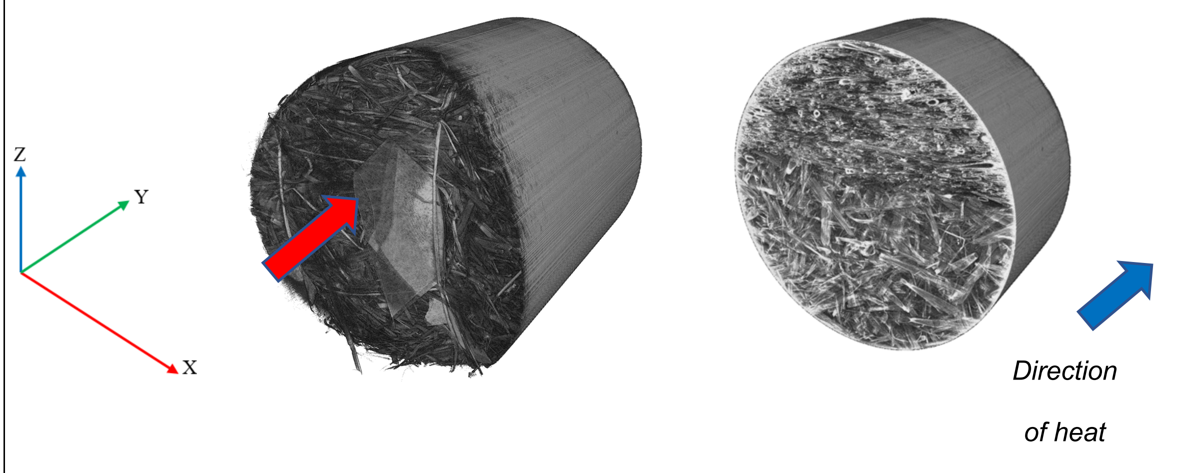
a) Oriented straw prototype

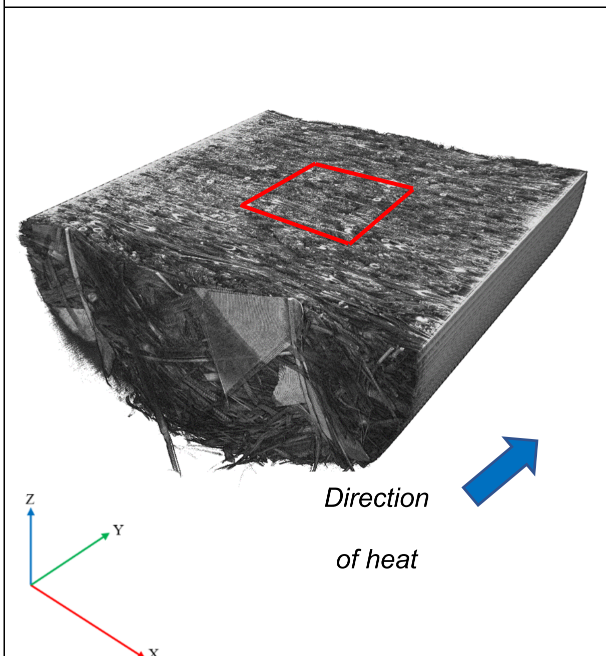
b) Three-dimensional representation of prototype 3

c) Cross section of prototype 3

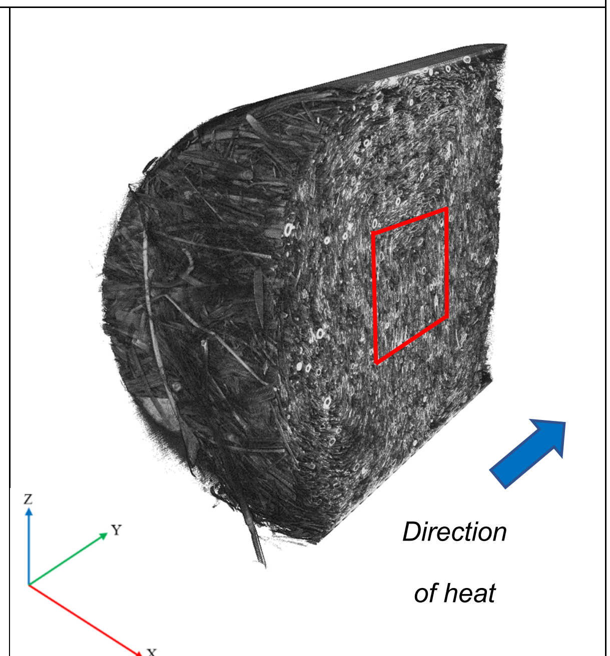
Figure 9. Half section of oriented straw bale

Additional analysis of the CT scans as performed with the larger agricultural bales previously discussed are shown in Figure 10. Here it is clear that the straw has been highly oriented perpendicular to the heat flow. The increased amount of longer thin lines indicates that there is considerable permanent deformation in the straw stems due to the secondary compression from the agricultural bale. A degree of deformation or damage done to the stems during the original baling process has been further exacerbated during the formation of the prototype. Some of this additional damage could possibly be reduced if the prototypes were to be produced at the source rather than secondary production from agricultural square bales.





Sub-volume cross section (xy axis)



Sub-volume cross section (yz axis)

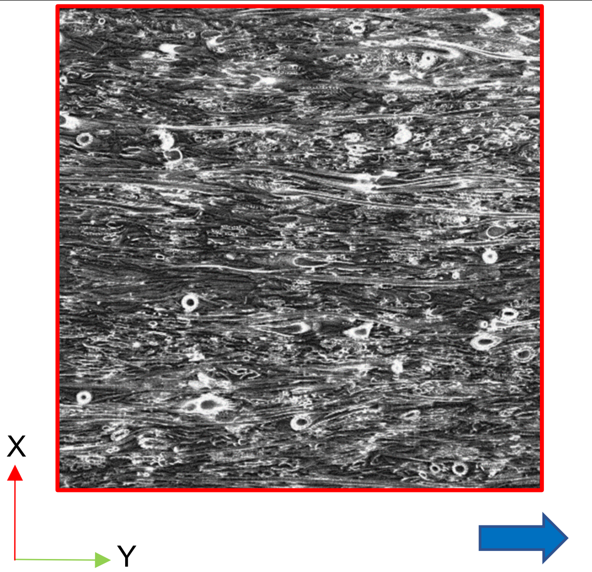
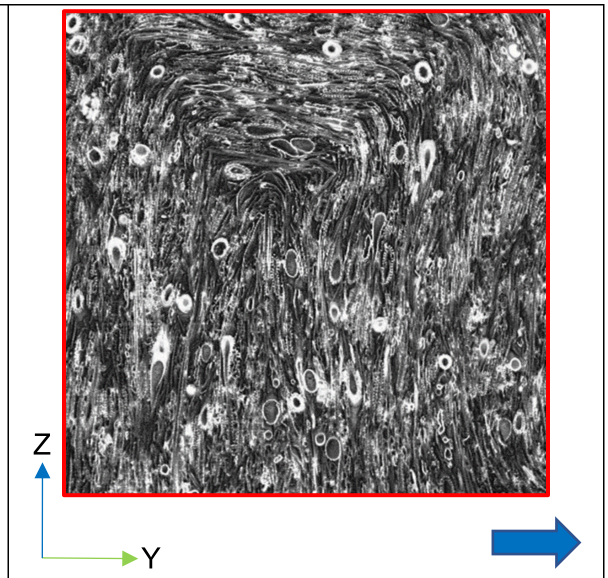
	
*Direction of heat flow **across** image, image looking through the depth of the prototype bale (horizontally)*	*Direction of heat flow **across** image, image looking through the length of the prototype bale (from the side)*

Figure 10. Prototype CT scan

CT scanning has been successfully applied to investigate the orientation of individual straw stalks within agricultural and prototype straw bales. There is clear evidence that modified prototype baling process has been successful in producing a product in which the straw is preferentially oriented to optimise thermal performance.

5.2 Impact of straw orientation on compressive resistance of prototype straw bales

The results of the compression testing on prototype bales are summarised in Table 1; for each series six repeat tests were performed. Specimens were tested with loading parallel and perpendicular to direction of bale compaction; these are similar to agricultural bale tests either on bed (parallel) and on edge (perpendicular). The stress-strain behaviour of each specimen is presented in Figure 11. As specimens do not display a distinct maximum or peak stress, but resistance increases as material densifies, the compressive resistance has been calculated at both 10% and 20% strains, as indicated by $\sigma_{10\%}$ and $\sigma_{20\%}$ respectively. The stress levels include the prestress from the steel plate placed on top of each specimen, whilst measured strain is only shown for loads applied above this initial prestress.

The two samples show slightly different responses under increasing stress levels, Figure 11. Those specimens subject to loading perpendicular to direction of the bale compaction load are generally stiffer than those load tested parallel to their compaction. The ‘perpendicular’ specimens exhibited an initially higher compression stiffness. In contrast the prototype bales load tested parallel to compaction initially showed lower stiffness, but this increased with load, although at both 10% and 20% strain the perpendicular specimens exhibited highest stiffness. Over the test range, following the initial stiffening, the response of the perpendicular specimens was quasi-linear, whilst for the parallel further deformation developed increasing stiffness with their densification. As indicated in Figure 11 the specimens with load in the parallel direction will continue to flatten the already oval shaped individual straws, whilst loads applied perpendicular are acting to correct this flattening effect.

The stress-strain responses are similar in shape to those reported previously for plain agricultural bales [Brojan & Clouston, 2014; King, 2007]. However, the values for stiffness measured in this study (79-118 kPa) were generally lower than range of values reported previously. For example, Brojan and Clouston (2014) reported values between 150 and 450 kPa for rye straw bales. The smaller scale of the prototype bales may have contributed to their apparent reduction in stiffness. For the intended application as infill insulation a lower stiffness is unlikely to significant. Interestingly the trend for bales tested on edge (or perpendicular to compaction direction) to be stiffer under load than bales laid flat (parallel to compaction direction) is also seen in the prototype bales.

Table 1. Summary of compression resistance test

Direction of compression relative to bale formation loading	Density	$\sigma_{10\%}$		$\sigma_{20\%}$		$E_{apparent}$	
	kg/m^3	kPa	CoV (%)	kPa	CoV (%)	kPa	CoV (%)
Parallel	126	13.3	5.32	28.9	13.5	79	19.9
Perpendicular	129	16.1	11.7	32.9	16.6	118	23.1

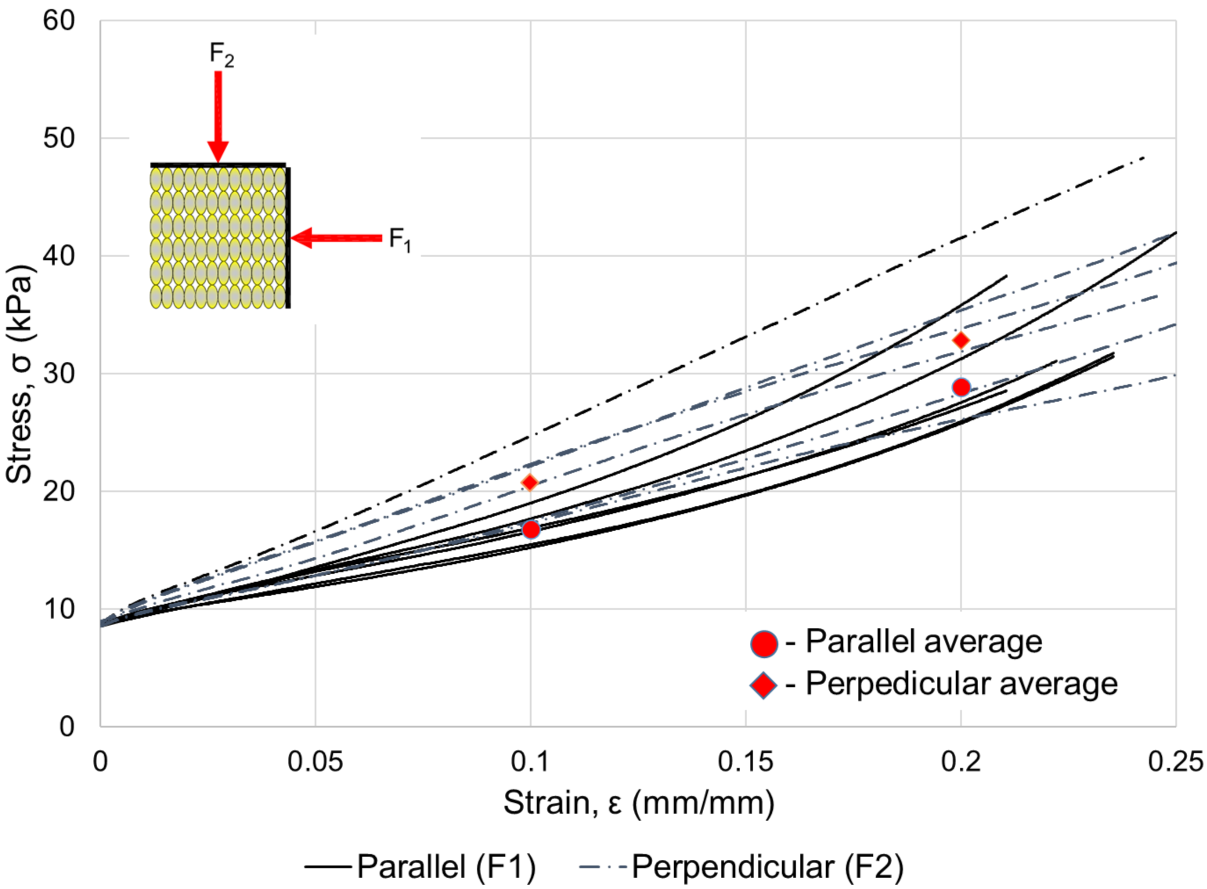


Figure 11. Stress-strain curves from compression tests

5.3 Impact of straw orientation of thermal performance

The average thermal conductivity results are presented in Table 2 for all specimens tested with straw oriented parallel and perpendicular to direction of heat flow. A Grubbs test for outliers indicates that all results are within acceptable tolerances and have 95% confidence intervals of ±0.0009 for both cases.

Table 2. Summary of heat flow meter tests for straw oriented parallel and perpendicular to the heat flux

Direction of straw relative to the heat flow	Bulk Density, ρ		Thermal Conductivity, λ	
	kg/m^3	CoV (%)	$W/_{m \cdot K}$	CoV (%)
Parallel (n=3)	126	9.27	0.078	0.46
Perpendicular (n=7)	129	12.9	0.056	17.5

The average thermal conductivity for the specimens tested with heat flow parallel to the direction of straw orientation was 0.078 W/mK. This is higher than average values quoted for agricultural bales laid flat or on edge (0.060 - 0.067 W/mK), which indicate that straws have been preferentially aligned in formation of the prototype bales. The average thermal conductivity (0.056 W/mK) of the specimens in which heat flow was perpendicular to straw orientation was 28% lower than the former case. This represents a 28% saving in insulation thickness to achieve equivalent thermal resistance. Given the variation and the small sample size a 95% confidence interval for a difference between two means was computed as (11%, 45%). This implies that even with the limitations of small sample size, considering the orientation would result in at least an 11% improvement in thermal conductivity but this could be as significant as 45%. The reduction in thermal conductivity was not as significant as reported for hand crafted small scale specimens in which all straw stalks are aligned perfectly perpendicular to the heat flow (0.043 - 0.045 W/m.K), but it is comparable with the thermal conductivity measured for agricultural bales when heat flow is parallel to the bale length [Yao, J., 2015]. As indicated by the CT scans of the prototypes, perfect orientation of all straws in during bale compaction is very difficult to achieve. However, there is scope for further refinement in upscaling the manufacture process to reduce thermal conductivity by controlling straw alignment.

The package style prototype straw bale insulation product are easier to handle than full-sized agricultural bales, and are more readily cut to fit non-standard spacings. Lengths can be produced to accommodate the width of conventional stud spacing and the bales are conveniently trimmed using on site equipment such as chop saw, or radial arm saw with a fine-tooth blade. Small gaps may be filled with the offcuts or by opening a bale. Production methods can be small on-site scale, and ideal for the self-build projects, whereas the introduction of large-scale balers designed to produce straw insulation would further reduce costs and increase availability.

6 Conclusions

This paper has presented work on the development and characterisation of prototype wheat straw bales produced specifically for use as a building insulation material. Work has included development of manufacture of prototype bales, CT scanning together with thermal and mechanical characterisation. The following conclusions may be drawn:

- CT scans of the agricultural bales showed a high degree of straw stems oriented in line with its thickness, which is parallel to the heat flow for an exterior wall.
- Equipment to produce the prototype bales has been successfully constructed to produce oriented bales for insulation, providing the basis for upscaling.
- Key factors determined in the production of the prototype oriented straw bales for insulation purposes included: Using minimum three string bale confinement; Maintaining

compressive pressure during manufacture; a maximum ratio of bale dimensions parallel with the baling twine of 2:1.

- CT scans of the prototype bales show that it is possible to achieve a degree of oriented stems perpendicular to the heat flow.
- By rebaling straw bales it is possible to improve thermal resistance and reduce necessary insulation thickness by approximately 28%.

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